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PLASMA MODIFICATION ASSOCIATED WITH PARAMETRIC INSTABILITIES DRIVEN BY INTENSE ELECTROMAGNETIC WAVES. (PART I) PARAMETRIC INSTABILITIES AND IONOSPHERIC MODIFICATION. (PART II)

Hans W. Hendel, et al

Princeton University

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PLASMA MODIFICATION ASSOCIATED WITH PARAMETRIC INSTABILITIES DRIVEN BY INTENSE ELECTROMAGNETIC WAVES
PART I

and

PARAMETRIC INSTABILITIES AND IONOSPHERIC MODIFICATION
PART II

Princeton University

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13. ABSTRACT
Part I: Collective plasma phenomena similar to those occuring in the ionosphere upon incidence of intense electromagnetic waves have been studied in laboratory Q-device plasmas. Two different propagation schemes have been investigated $\vec{E} \parallel \vec{B}$ $(k_\parallel \geq k_\perp)$ and $\vec{E} \perp \vec{B}$ $(k_\parallel \ll k_\perp)$.

Abstract Part II: Parametric instabilities, excited in the ionosphere by high power, HF transmitters with a frequency below the maximum ionospheric plasma frequency, produce nonlinear energy absorption and enhanced scattering of electromagnetic radiation which has been detected by the Arecibo Thomson-scatter radar. This paper reviews and extends both the linear and nonlinear saturation theory of parametric instabilities within the ionospheric contect. Calculations are presented of the magnitude of the nonlinear energy absorption and of the angular dependence, frequency spectrum, and intensity of scattering from instability-created density fluctuations.

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PART I

Hans W. Hendel

and

PARAMETRIC INSTABILITIES AND IONOSPHERIC MODIFICATION
PART II

C. R. Oberman
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Joseph J Simons
For Vincent J. Coyne
RADC Project Engineer

Fred C. Wilson
RADC Contract Engineer

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Plasma Modification Associated with Parametric
Instabilities Driven by Intense Electromagnetic Waves

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ABSTRACT

Collective plasma phenomena similar to those occurring in the ionosphere upon incidence of intense electromagnetic waves have been studied in laboratory Q-device plasmas. Two different propagation schemes have been investigated $\vec{E}||\vec{B}$ ($\vec{k}_{\parallel} \gtrsim \vec{k}_{\perp}$) and $\vec{E} \perp \vec{B}$ ($k_{\parallel} << k_{\perp}$).

The absorption of electromagnetic waves with $E||B$ at a frequency close to the plasma frequency and an intensity above that for the threshold of the parametric ion acoustic decay instability, is enhanced above that predicted from a model based purely on electron-ion collisional dissipation. Instability onset power is observed to agree well with infinite plasma theory. The anomalous absorption, or the effective collision frequency, in the unstable region is proportional to the square of the electric field driving the instability, in agreement with theory. This wave-enhanced dissipation leads to intensive electron and ion heating of close to a factor of 10 for a power level an order of magnitude above threshold. Simultaneously the plasma density is reduced, which appears to be due mainly to equilibrium pressure change resulted from heating. Due to the

strong dependence of the instability parameters on both temperatures and density, the details of the instability behavior are complicated and not well understood.

For a perpendicularly traveling pump wave, the incident electromagnetic wave is observed to convert to an electrostatic electron plasma wave propagating nearly perpendicular to $B(k_{\parallel}/k_{\perp} \simeq 10^{-2})$ the Trivelpiece-Gould mode. The parametric ion cyclotron instability, also traveling nearly perpendicular, is identified by measurements of ω and k. Measured onset power and growth rates are in agreement with theory. In the presence of the parametric ion cyclotron waves, intense ion heating is observed with a temperature increase of a factor of ~ 50, for the observed power ~ 20 times the power at onset.

I. SUMMARY

The purpose of the experimental effort at Princeton University is to study in laboratory plasma, the collective interactions relating to the enhanced absorption of electromagnetic waves in the ionospheric plasma recently observed in the ionospheric modification program. (A review paper on "Laboratory Parametric Instability Experiments" is in print in Comments on Plasma Physics, see enclosure.) The experiments have been performed in Q-device plasmas, which have comparable ion and electron temperatures, similar to the ionospheric plasma. Three groups of experiments have been performed, with parallel electric field excitation, with perpendicular electric field excitation and scattering of electromagnetic waves off the parametric instability.

In the parallel electric field case the onset of instability occurs for electric fields comparable to those predicted by infinite plasma theory. The instability is observed having an unstable component in the ion acoustic range and an unstable low frequency side band of the pump, both destabilizing simultaneously. Anomalous, enhanced absorption is observed when the incident power is larger than the value for instability onset. The enhanced collision frequency based on wave-particle interactions was measured by using cavity Q determinations and was found to be proportional to the square of the pump electric field, in agreement with a theory based on nonlinear ion Landau damping.

(This work was presented in Phys. Rev. Lett. 29, 634 (1972), see enclosure.) The enhanced dissipation leads to large absorption of power in the plasma. Measurements of electron and ion temperatures show significant increase, of close to an order of magnitude for powers ten times above the onset power, with the electron temperature at the higher powers a few times above the ion temperature. Thus the sound wave is always strongly damped. The intense heating leads to a reduction of the plasma density, which, however, appears to be mainly related to changes in the axial transport properties. Due to the strong dependence of instability properties on both electron and ion temperatures and on the density, the detailed behavior of the instability was found to be complicated and is not yet understood.

For a perpendicularly traveling pump wave, measurements have been performed which indicate parametric electrostatic ion cyclotron instability and concomitant intense ion heating. An electromagnetic pump wave is launched from outside the plasma column and is observed to convert to an electrostatic plasma wave inside the plasma column, traveling nearly perpendicular ($k_\parallel/k_\perp = 10^{-2}$) to the magnetic field as Trivelpiece-Gould mode. The ion cyclotron wave, also propagating nearly perpendicular at onset, is identified by measurements of ω and k. The measured threshold power and growth rates are in agreement with a linear theory which takes into account cyclotron damping for the ion wave and collisional damping for the electron plasma wave.

Beyond onset, intense heating is observed, with a temperature increase of a factor of ~ 50 for powers ~ 20 times above onset power.

For the purpose of performing scattering experiments, a special Q-device has been built. Scattering measurements have been obtained. However, the wavelengths observed were considered to be much longer than expected and scattering work will be taken up again when the instability is better understood.

II. INTRODUCTION

The purpose of the experimental effort at Princeton University under ARPA sponsored Contract No. F30602-72-C-0053 is to study in controlled laboratory experiments the collective effects and their results relating to the present ionospheric modification program. Anomalous absorption of incident radio frequency power and simultaneous heating of the ionospheric plasma observed at Boulder and Arecibo could be explained based on the destabilization of parametric ion acoustic decay instabilities. Although extensive theoretical work on parametric instabilities had been reported, and numerical simulation had indicated concomitant electron heating, the causal, direct relationship between well identified parametric instability, enhanced resistivity, and plasma heating had not been demonstrated in prior experiments. [For a review of the experimental situation see Comments on Plasma Physics and Controlled Fusion <u>1</u>, 115-141 (1972).]

According to theory, the parametric instability is generated by an incident high-frequency field at a frequency close to the plasma frequency, which decays into an electrostatic wave and an ion acoustic wave. The ion acoustic wave has a frequency much lower than the plasma frequency and the electrostatic electron plasma wave is predicted to appear close to the pump frequency, downshifted by the acoustic frequency. In the ionosphere, the ion acoustic wave and therefore the parametric instability is heavily damped due to the low ratio of electron to ion tempera-

tures, which is close to one, indicating strong ion Landau damping. It was therefore imperative to use a similar plasma for the laboratory simulation experiments, i.e., a Q device plasma, where the equilibrium temperature of the ions is higher than that of the electrons.

III. EXPERIMENT

The experimental work was performed on the Princeton Q-1, Q-1T, and Q-3 quiescent, alkali metal, surface ionization plasma devices. The magnetically confined plasma ($3 \leq \omega_{ce}/\omega_{pe} = 30$) consists of ions produced by surface ionization of four Cs or K atomic beams incident on hot tungsten ionizer plates at both ends of the plasma column and of thermionic electrons emitted from these plates. T_i is typically $3T_e$, where $T_e = 0.2$ eV. $\nu_{ei} \approx \omega_{pi} \approx 3$MHz, and $10^9 < n < 2 \times 10^{11}$. The three-cm-diam end plates are aligned perpendicular to the magnetic field. The plasma columns are approximately one meter long. The alkali-metal vapor pressure is cryogenically reduced to below 10^{-7} Torr, so that the plasma is fully ionized. No voltage is applied to the plasma column. The ion density can be kept constant with a deviation of less than 1%.

The plasma diagnostics consist of Langmuir probes, ion temperature probes, high frequency probes, and microwave cavity. Langmuir probes and the cavity measure both density and electron temperature. The electron temperature can also be determined from floating potential measurements. Special probes with high-frequency response measure the instability frequency spectrum. The ion temperature can be determined using probes after I. Katsumata and M. Okazalki, Japan J. Appl. Phys. 6, 123 (1969). Probes can be used in 20 positions throughout the plasma and all probes can be moved radially in and out of the plasma column. Axially movable probes allow motion along a B-field line over 20 cm. The magnetic field can be varied from zero to seven

kG, however, large plasma losses set in below approximately 2 kG. $T_i \simeq 3T_e \simeq 0.2$ eV. $\nu_{ei} \simeq \omega_{pi} = \omega_{LH}$.

The excitation of the parametric instability was done in a number of ways, by resonant cavity, grids or grid, single wire probes, coupling wires or rings surrounding the plasma, and by long capacitive electrodes on the outside of the plasma column.

Due to the importance of scattering of electromagnetic waves off the instability in the ionospheric experiments, a special setup was built for scattering in the laboratory experiments. This device has an oversized magnetic field coil surrounding a scattering chamber and two 8 mm microwave horns. Instability wavelength and frequency are determined by varying transmitter and receiver horn angles and measuring amplitude and frequency, where the scattering angle, and shifted frequency are determined by:

$$\omega_{\text{transmitter}} = \omega_{\text{scattered}} + \omega_{\substack{\text{pump;}\\ \text{instability}}}$$

$$\vec{k}_{\text{transmitter}} = \vec{k}_{\text{scattered}} + \vec{k}_{\substack{\text{pump;}\\ \text{instability}}} \quad .$$

The 100 mW, 35 GHz klystron transmitter is tunable over a range of approximately 2 GHz, and the receiver has a fixed local oscillator frequency, with a Fabry-Perot rf cavity to reduce the amplitude of the unshifted frequency of the transmitter. The 9 dB noise figure receiver system consists of a doubly balanced microwave mixer, with a 120 dB gain 30 MHz IF strip. A lock-in

amplifier technique permits 30 dB enhancement above the noise level. A circuit was devised to stabilize to $\approx$ 1 kHz the transmitter-receiver frequency shift to the pump frequency. This frequency is monitored and scanned to obtain the excited instability spectrum near the pump frequency. The scattering system, unlike a conventional spectrum analyzer is much less likely to become overloaded when the frequency scanned is at the pump frequency.

Results from the scattering apparatus are difficult to interpret, with our present understanding of the parametric instability. Strong scattered signals with cross section $\sigma \approx 10^4 \sigma_{\text{Thomson}}$ are observed with frequency shift from the pump less than $\approx$ 300 kHz. Parallel wavelength measurements result in multiple peaks in some cases, indicating the presence of more than one wavelength. The measured wavelengths, however, do not vary (with respect to changes in density or pump frequency) in the expected manner. Thus the scattering has been temporarily suspended pending a more thorough understanding of the parametric instability.

IV. RESULTS

A. Measurements of Enhanced Absorption of Electromagnetic Waves and Effective Collision Frequency Due to Parametric Decay Instability.

Our results on anomalous absorption have been published in some detail [Phys. Rev. Lett. 29, 634 (1972)], and we will only briefly summarize the work. A microwave cavity is used to excite the instability and, from the cavity-Q, to obtain information on the dissipation of the electromagnetic energy in the plasma. A number of important results arose from this work. The onset of the parametric decay instability leads to enhanced absorption. The onset electric field value agrees with that of linear theory. The additional power absorbed in the plasma results in electron heating. (Ion temperature probes were not available for this experiment.) Above onset the relation between measured pump field amplitude and absorbed power can be explained in terms of an effective collision frequency, which depends on the square of the pump field. This result is in agreement with a theory based on nonlinear ion Landau damping.

Several significant considerations can be derived from these experiments. Firstly, our results confirm predictions of the linear and nonlinear theories of the parametric instability. Secondly, the instability can be excited over a wide range of parameters and frequencies, in finite-size plasma columns as a

result of the Trivelpiece-Gould dispersion relation for plasma waves in such columns. Thirdly, since the instability can be destabilized at very low pump field intensities at onset (drift over thermal energy ≈ 5%), parametric effects may play a significant role in many rf heating methods. Finally, this work presents conclusive evidence for the existence of a dissipation mechanism for electromagnetic waves not based on particle-particle collisions but on wave-particle interactions, which can lead to power absorption much larger than the dissipation due to classical rf heating.

B. Plasma Heating by the Parametric Ion Acoustic Decay Instability

Measurements of plasma heating due to the instability are of major importance for a number of reasons. For fusion purposes, any new heating mechanism would be significant. For the case of ionospheric modification, and, in general, to understand better the steady state and the nonlinear saturation stage of the instability, possible heating of both types of particles must be considered, since the temperature determine the damping. In addition, the elevated temperature, the pump field, the instability amplitude or effects resulting from it, may vary the transport properties of the plasma and produce plasma density changes, which in the worst case could lead to quenching of the instability. We have therefore performed detailed measurements of the ion and electron temperatures as a function of pump field and instability amplitude. Since these results have not been reported yet in detail, they will be discussed in greater length and figures will be included.

Figure 1 shows the experimental arrangement for the heating measurements. The pump field is applied off-center (axially) to the plasma column, and changes of the plasma parameters can be measured throughout the plasma. Figure 2 gives ion and electron temperatures, floating potential, and plasma density, as a function of absorbed power. As the power is increased, for the stable plasma, the plasma parameters are only slightly changed. Onset of the instability and increasing of the instability amplitude lead to an increase in both electron and ion temperatures, with the electron temperature always somewhat higher than the ion temperature. However, the temperature ratio is never very different from one, so that the ion sound wave never becomes strongly destabilized. The ion temperature increase cannot be due to collisional effects since at the higher temperatures the time for collisional temperature relaxation is much longer than the ion lifetime in the plasma, which is of the order of a few milliseconds. Thus the ion heating must be due to wave-particle interactions. Theories of parametric instabilities have generally not taken this effect into consideration. We notice that in our plasma the electron confinement time is given by the diffusion time across the plasma length, which is by three orders of magnitude faster than the ion lifetime, so that the electron temperature is suppressed by the large temperature sink at the ends of the plasma column, the end plates. Thus, the ion temperature may even be expected to be higher for cases of better electron confinement. The ion temperature distribution across the plasma

radius was measured to be approximately constant, Fig. 3, as is expected due to the long ion confinement and the large ion Larmor radius, which act to smooth out temperature gradients.

In Q-device plasmas, the equilibrium ion temperature is largely determined by the ion confining sheath at the end plates, which, for an electron rich plasma, accelerate the ions into the plasma and lead to an ion temperature a few times higher than the electron temperature, the latter being comparable to the end plate temperature. Thus, in the present case we must ask whether the equilibrium, especially the sheath, could have been affected by the pump or instability in a way which would increase the ion temperature. Plasma potential measurements have been made which show that the ion accelerating sheath-potential is reduced in the presence of the instability, so that the initial temperature at which the ions are injected into the plasma is reduced. A similar argument holds for possible heating due to the shear electric field at the plasma edge. Thus, we concluded, that the ion heating cannot be due to changes in the equilibrium caused by instability effects. The specific mechanism which leads to the ion temperature increase by the instability is not known. Figure 6 shows decay of the ion temperature after a heating pulse. This decay time is consistent with the ion lifetime.

Also shown in Fig. 2 is the reduction of the density with increasing pump power. By measuring the radial distribution of the density it could be shown that the density reduction is not due to increased radial transport but to changes in the parallel

transport properties. The reduction of density both inside and outside the plasma column is shown in Fig. 4, which for comparison also contains a plot of the radial density distribution for a case where radial transport is dominant. The abrupt changes in absorbed power are due to instability mode changes, as can be seen from the changes in the spectrum.

These measurements indicate the complexity of parametric instability experiments. As the absorbed power is increased, both the ion and electron temperatures and their ratios are changing often abruptly, due to abrupt mode changes. Simultaneously, the density varies, so that the important parameter $\omega_{pump}/\omega_{pe}$ is also a variable. For ionospheric modification one might expect that if the interaction time is long eneough for heating to become important, the plasma density may be decreased and the interaction region may shift to a region where the resonance conditions are fulfilled better. Such quenching of the instability is shown in Fig. 5.

V. PARAMETRIC ION CYCLOTRON WAVES AND ION HEATING

In this experiment, effects of waves propagating perpendicular to the magnetic field have been studied. Here we report detailed measurements of electrostatic ion cyclotron waves driven parametrically unstable by nearly perpendicular propagating electron plasma waves, and of the concomitant intense plasma heating. The measurements include:

1. Measurements of the conversion of an incident electromagnetic wave into an electrostatic wave (in the presence of the plasma). This wave is identified as a Trivelpiece-Gould mode.
2. Frequency and wave number selection rules for the parametric process.
3. The dispersion of the ion cyclotron instability.
4. Instability threshold and growth rates, and amplitude ratio of the decay waves. These results are in agreement with a linear theory of the parametric ion cyclotron instability driven unstable by strong transverse electric fields, and with the Manley-Rowe relations, respectively.
5. Ion and electron heating.

In addition, enhanced thermal fluctuations in the pre-onset regime, pump field depletion associated with instability onset and a decay process involving a low frequency instability at a frequency below the ion cyclotron frequency were observed, the threshold conditions for this latter instability being consistent with that for a parametrically driven second ion cyclotron instability.

Calculations show that there exist two branches of ion cyclotron waves, the long parallel wavelength ($k_\parallel/k_\perp \ll 1$) and the obliquely propagating mode ($k_\parallel \sim k_\perp$). Their frequencies for minimum threshold conditions are:

I. $k_\perp^2 C_s^2/\Omega_i^2 \ll 1$

$$\text{a)} \quad \omega^2/\Omega^2 = 1 + k^2C_s^2/\Omega^2 \qquad (k_\parallel \ll k_\perp) \tag{1a}$$

$$\text{b)} \quad \omega^2 = k_\parallel^2 C_s^2 \qquad (k_\parallel \sim k_\perp) \tag{1b}$$

II. $k_\perp^2 C_s^2/\Omega_i^2 \gg 1$

$$\text{a)} \quad \omega^2 = k^2 C_s^2 \qquad (k_\parallel \ll k_\perp) \tag{2a}$$

$$\text{b)} \quad \omega^2 = \Omega^2 (k_\parallel^2/k^2) \qquad (k_\parallel \sim k_\perp) \quad . \tag{2b}$$

The corresponding threshold condition for these instabilities can be expressed by a single criterion:

$$(k\cdot\varepsilon)^2 = 4k^2 v_e^2 \left(\frac{kv_e}{\omega_{pe}}\right)^2 \frac{\bar{\nu}_e}{\omega_o} \frac{\nu_i}{\Omega_i} \frac{T_e}{T_i} \quad , \tag{3}$$

where k is the instability wave number, ε is the particle ac drift, v_e is the electron thermal velocity, $\bar{\nu}_e \equiv \nu_e\ (k_\parallel^2/k_\perp^2)$ where ν_e relates to collisional damping of the electron plasma wave, and $\nu_i \equiv 2\sqrt{\pi}\,(k^2v_i^2/\Omega)(\omega/k_\parallel v_e)\ \exp[-(\omega - \Omega)/k_\parallel v_i]^2$ denotes ion cyclotron damping. In the regime of $\omega_{ce}/\omega_{pe} \gg 1$, the coupling mechanism is $E \times B$ for the ion cyclotron wave (branch a) and electron parallel motion due to $E_\parallel$ for the second ion cyclotron wave (branch b).

Figure 7 shows the decay process described above. The $\omega_{pe}\cos\theta$ pump wave decays into another electron plasma wave and one of the two ion cyclotron branches. Measured threshold conditions agree with those of Eq. (3). Figure 8 shows the measured frequency as a function of the magnetic field. The ion cyclotron wave is calculated from Eq. (2b), using the measured $k_\theta/k_\perp \approx m/r=6$. The ion temperature and peak instability amplitudes as a function of rf power are shown in Fig. 9. The measured electron temperature is of the order of T_i. At still higher power levels, severe plasma losses occur.

In conclusion, this work shows mode conversion from an electromagnetic pump wave to an electrostatic plasma wave. Thus, in implementing rf heating by a particular coupling method (waveguide, cavity, launched waves) mode conversion and thus accessibility must be considered. The mode structure of the electromagnetic plasma wave must be consistent with the geometric constraints of the entire plasma. Moreover, over a wide range of plasma density, magnetic field and ion mass, the destabilization of the parametric ion cyclotron instability leads to intense ion heating.

VI. CONCLUSIONS

What significant new results have been obtained in the experimental work performed under the present contract and what conclusions can be derived which are of direct impact in regard to the ionospheric modification experiments?

The onset of both the parametric ion acoustic instability and of the parametric ion cyclotron instability were observed for electric fields in agreement with predictions. For the case of the ion acoustic decay instability, anomalous absorption was observed and found to indicate an anomalous collision frequency proportional to the square of the pump field, in agreement with a theory based on nonlinear ion Landau damping. In both cases, the unstable frequency spectrum and wave numbers agree with expectations.

For both of these parametric instabilities, intense ion heating is observed, which is somewhat unexpected for the case of the ion acoustic instability since ion sound amplitudes are so low. The temperature increases by an order of magnitude for steady-state absorbed powers approximately an order of magnitude above the onset power. The ion temperature decay times agree with the ion confinement times, as expected. In the case of the ion acoustic decay instability this increase of the ion temperature has the result that the electron-ion temperature ratio never becomes much greater than 1, so that the sound waves never become strongly undamped.

Thus, in regard to ionospheric modification experiments, the behavior of the anomalous collision frequency can be considered predictable on the basis of these experiments. The effects of ion heating by the instability have, to our knowledge, not been included in any theory of parametric instabilities. Since this effect should occur on a time scale comparable to the growth rate, ion heating may affect the instability parameters importantly. On a much slower time scale, the effects of the pressure changes due to ion heating must be considered. Density gradients both in the parallel and the perpendicular direction may appear as a result of heating and the local value of ω/ω_{pe} may be reduced so that the region of maximum power absorption may vary.

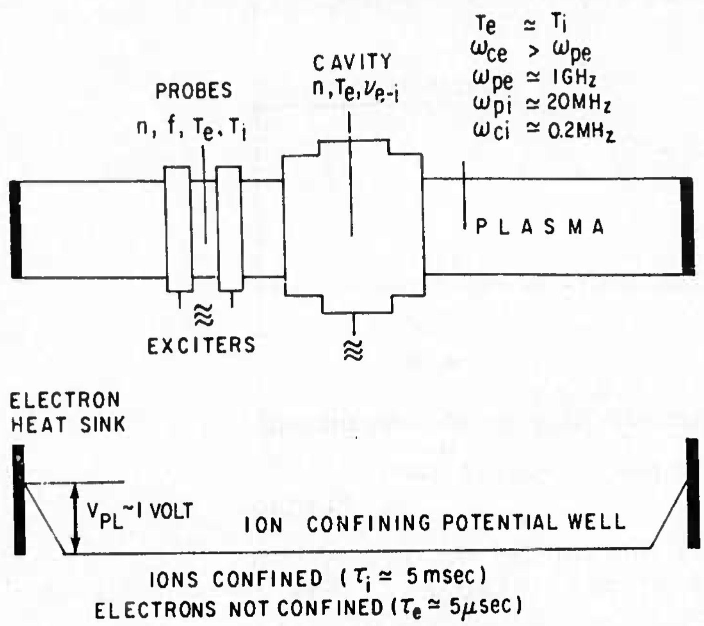

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Fig. 1. Q-1 machine configuration.

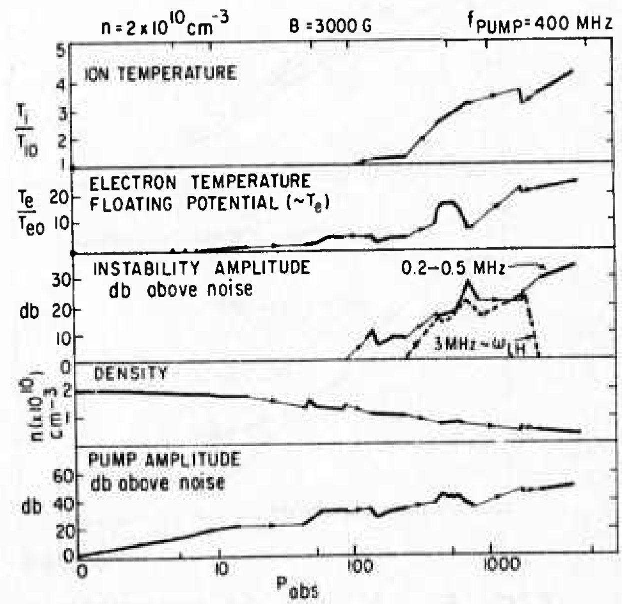

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Fig. 2. T_i, T_e, instability amplitude (at ω_{pe}), density, pump potential amplitude, as function of pump power P_{abs} in mW (circuit losses included).

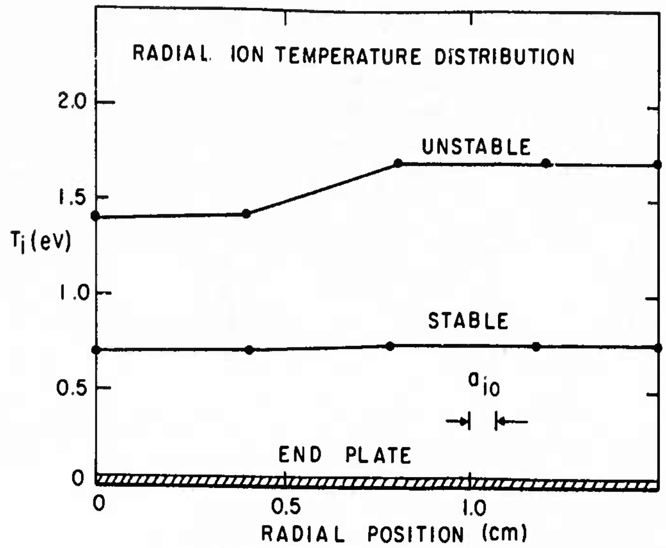

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Fig. 3. Radial variation of T_i, RF on (unstable) and RF off (stable). The ion Larmor radius is indicated by a_{io}.

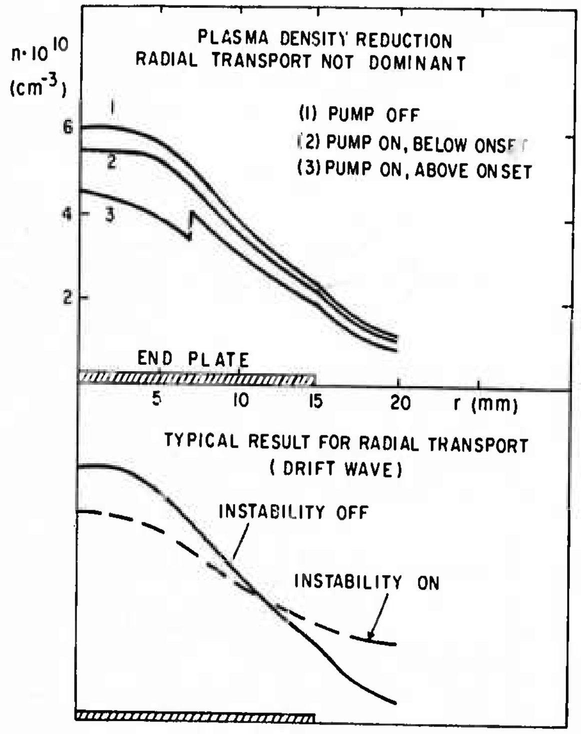

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Fig. 4. Effect of parametric instability on radial plasma transport.

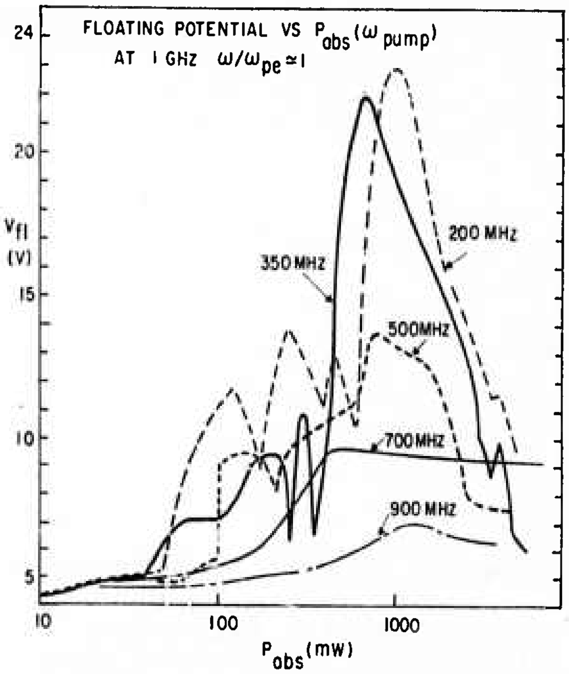

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Fig. 5. Variation of floating potential with absorbed power.

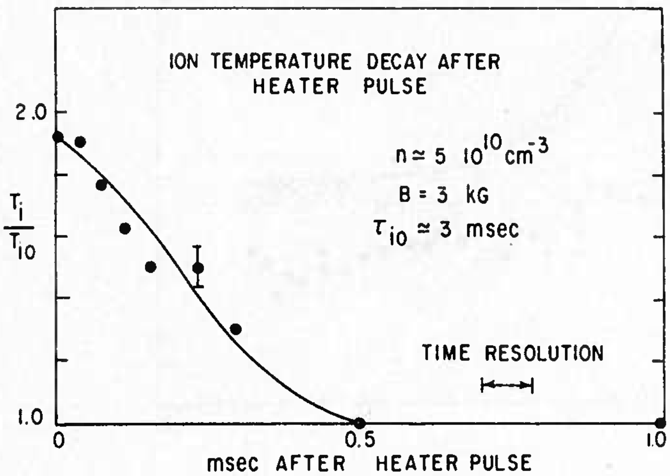

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Fig. 6. Ion temperature decay after heater pulse.

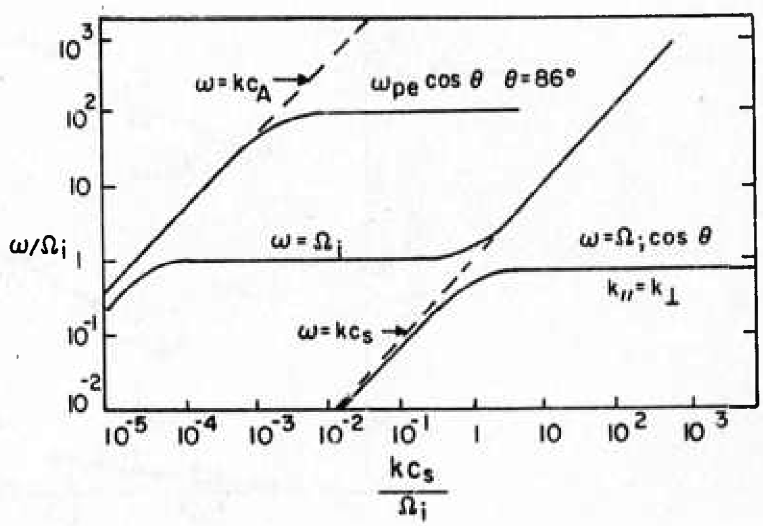

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Fig. 7. Dispersion relation of the plasma wave (pump) $\omega_{pe}\cos\theta$ and the ion cyclotron wave (low-frequency component of the decay wave), plotted in ω/Ω_i vs kC_s/Ω_i.

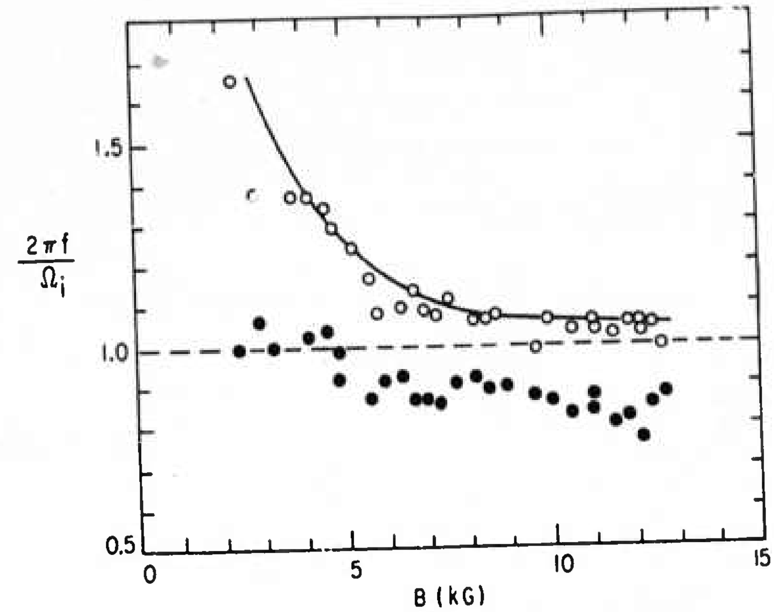

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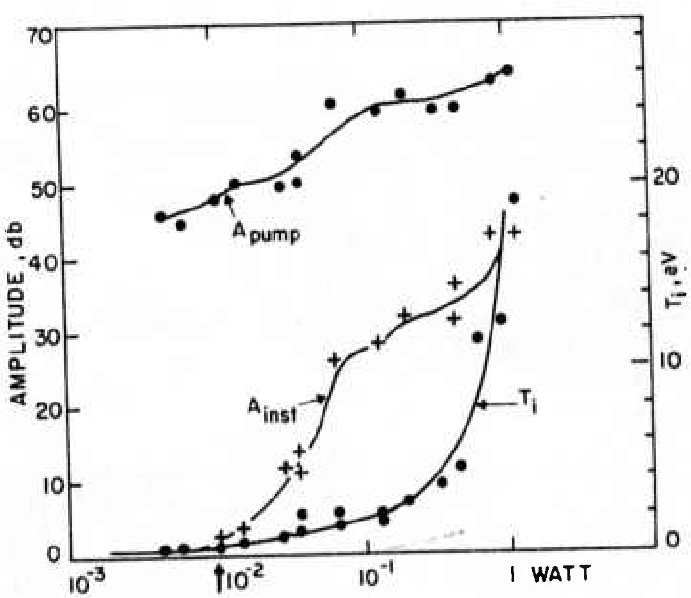
Fig. 8. Measured frequency of the low-frequency component of the decay wave normalized to ion cyclotron frequency vs magnetic field for C_s plasma. The curve is calculated from the linear theory.



733151

Fig. 9. Measured ion temperature and instability amplitude as a function of pump power. C_s plasma, $B = 8.6$ kG, $n = 2 \times 10^{10} cm^{-3}$.

Parametric Instabilities and Ionospheric Modification

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Parametric instabilities, excited in the ionosphere by high power, HF transmitters with a frequency below the maximum ionospheric plasma frequency, produce nonlinear energy absorption and enhanced scattering of electromagnetic radiation which has been detected by the Arecibo Thomson-scatter radar. This paper reviews and extends both the linear and nonlinear saturation theory of parametric instabilities within the ionospheric context. The new elements are a modification at the emission term to include the effects of nonlinear plasma waves and a numerical integration of the wave-kinetic equation to find the saturation state of parametric instabilities assuming only that the wave intensity has axial symmetry about the pump field in wavenumber space. Calculations are presented of the magnitude of the nonlinear energy absorption and of the angular dependence, frequency spectrum, and intensity of scattering from instability-created density fluctuations. In the present experiments, the nonlinear processes are predicted to absorb roughly 30% of the radiowave energy incident on the ionosphere. This energy is deposited in the high-energy tail of the electron velocity distribution and causes enhanced airglow. The scattered radiation has a frequency shift almost equal to the modifier frequency and its intensity depends strongly on the angle between $\vec{k}$ and $\vec{E}_o$, $\vec{k}$ being the wave vector of the

plasma wave responsible for the scattering and $\vec{E}_o$ the pumping electric field produced by the modification transmitter. Because the instabilities occur only with O-mode transmissions, the direction of $\vec{E}_o$ is close to the geomagnetic field. The angular-dependence result rests on a combination of two-dimensional saturation calculations and plasma-wave refraction due to propagation in the inhomogeneous magnetoactive ionospheric plasma. For example, the plasma waves responsible for the scattering observed at Arecibo are found to be nonlinearly stabilized and roughly 10^4 times less intense than plasmaswaves propagating within 20° of the geomagnetic field. Thus the scattering observed at Arecibo, although intense by Thomson scatter standards is predicted to be ~ 40 dB below the scattering observable in the most favorable geometry. Lastly, new aeronomy experiments made possible by parametric instabilities are discussed.